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Long-Baseline (> 1000 km), Sub-Decimeter Kinematic Positioning of Buoys at Sea, with Potential Application to Deep-Sea Studies

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BIOGRAPHY

Dr. Oscar L. Colombo works on applications of space geodesy, and has developed and tested methods for highly accurate, very long baseline, kinematic GPS positioning. He has a degree in Telecommunications Engineering from the National University of La Plata, Argentina, and a Ph.D in Electrical Engineering from the University of New South Wales, Australia.

Dr. Alan G. Evans has been working in Global Positioning System (GPS) applications at the Naval Surface Warfare Center, Dahlgren Division (NSWCDD) since 1981. He received the B.S.E.E. degree from Widener University in 1964, and the M.S. and Ph.D. degrees from Drexel University in 1967 and 1971, respectively.

Dr. Maria Isabel Vigo-Aguiar is a Professor at the Department of Applied Mathematics of the University of Alicante, in Spain. She works on applications of artificial satellites in geodynamics, and is interested in the use of GPS for precise static and kinematic positioning. She received her first degree and her doctorate, both in mathematics, from the Universities of Salamanca and Alicante, respectively.

Dr. Juan Manuel Ferrandiz is Head of the Department of Applied Mathematics of the University of Alicante. His research interests include the study of earth rotation and orientation in space, plate tectonic motions, and the use of GPS and other space systems for precise positioning.
He got his first degree and Doctorate in Mathematics from the University of Zaragoza.

Dr. Juan Jose Martinez-Benjamin is Professor in the Department of Applied Physics, ETSECCPB, from the Polytechnic University of Catalonia (UPC). He is working on satellite altimetry and altimeter calibration using GPS in buoys, and is a member of the Science Work Team for the Topex/Poseidon and Jason-1 altimeter missions. He received the degree of Doctor in Industrial Engineering from UPC, and of Docteur de Troisieme Cycle en Sciences Physiques from the University of Paris VI.

ABSTRACT

GPS data from two experiments in positioning buoys at sea have been processed using a precise, long-range, differential, kinematic technique. In each case the data were collected for more than three hours both at a buoy and at a nearby coastal site (in Llafranc, Spain, and in Duck, USA) at a high rate (1-2 Hz), along with measurements from neighboring tidal stations, to verify the estimated heights. A precise, short-range trajectory was computed for each buoy, relative to the nearby coastal site. The trajectory of each buoy was re-calculated relative to distant reference sites, some more than 1000 km away (IGS stations in Europe, CORS stations in the USA). In both cases the 3-dimensional (r.m.s.) difference between short and long-range position fixes was less than 10 cm over three hours. The use of a simple constraint on the buoy's mean height variability greatly speeded up the convergence of the navigation Kalman filter.

INTRODUCTION

The precise positioning with GPS of buoys in the deep ocean can be of great help to those studying tides, waves and currents, charting the sea-floor and the marine environment with advanced forms of remote sensing, or calibrating satellite-born altimeters, to map with them the sea surface. To do so in real time may help detect tsunamis far from the coast, giving earlier warning to those at risk. Used with ships, the same technique may enable safer and more efficient marine navigation.

In the deep ocean, potentially devastating tsunami waves (generated by sudden movements of the ocean floor such as earthquakes, landslides, and volcanic explosions) travel at speeds of about 700 km/h as small, gently rising waves of up to 1 m in height. They are hard to detect, because they have periods of 10-30 minutes, and wavelengths of hundreds of kilometers. As they approach the coast, these waves become shorter and higher as the ocean gets shallower. By the time they arrive on shore, they may have become walls of water many meters high, travelling at great speed and causing catastrophic flooding. Tsunami waves are monitored with a combination of land-based tide-gauges and seismometers. In the US, Federal and State government agencies cooperate in the National Tsunami Hazard Mitigation Program [1]. The monitoring devices are located at coastal sites. In order to provide a much earlier warning of an approaching tsunami, NOAA has under way its research project for Deep-ocean Assessment and Reporting of Tsunami (DART), using buoys in the high seas, acoustically linked to sea-floor pressure gauges [2]. The buoys relay the gauge data to a central land site by satellite radio links. If buoys with GPS receivers could be used to monitor short-term changes in mean sea level larger than 10 cm, they could also be used to detect tsunami, possibly at a lower cost.

Another application under study is the use of GPS on buoys to get "ground-truth" observations of mean sea height to validate those from satellite-born altimeters, calibrate those instruments, and correct their biases. Satellite altimetry, primarily a technique for mapping the sea surface repeatedly and worldwide, has proven invaluable for studying ocean currents and tides, climate change, and the Earth's gravity field.

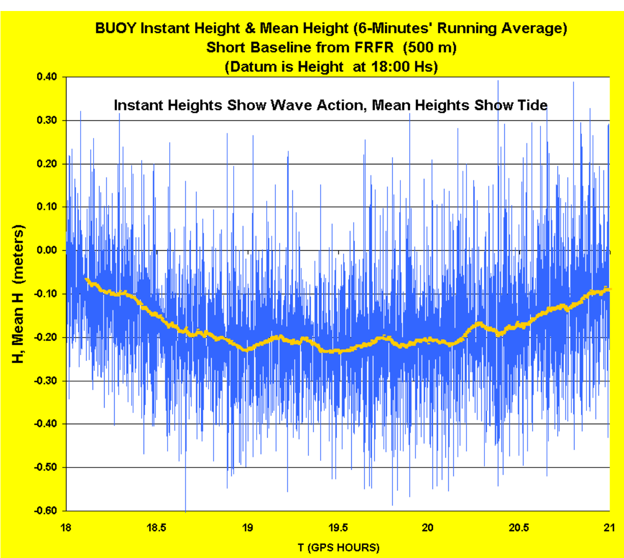

Figure 1. Waves and tide during test at Duck, North Carolina, as observed with GPS on a buoy. Short-baseline differential solution, with L1 and L2 carrier phase ambiguities resolved.

Differential, kinematic GPS positioning of buoys relative to nearby coastal stations has been used in the past to study tides and investigate its potential for monitoring sea-level change.

As shown in Figure 1, a running average of the observed instantaneous buoy height, with a window of 5 or 6 minutes duration, largely eliminates the short-term fluctuations due to ordinary waves (with periods of 5 to 30 seconds). This reveals more gradual changes in water level, such as tides and deep-ocean tsunami [3]. The accuracy is a few centimeters. Such accuracy is possible because the differential effect of the ionosphere on the data cancels itself out on the short baselines used (less than 10 km), making it possible to resolve exactly the carrier phase ambiguities.

For deep-sea applications, the buoys can be hundreds and even thousands of kilometers from the nearest land site. The first author has been developing and testing methods for sub-decimeter kinematic positioning over just such long baselines [4], [5], [6].

BUOY TESTS AT SEA

The long-range kinematic technique has been used to analyze two sets of data from receivers with antennas on buoys. One of the sets was collected off the coast of Catalunya, in Spain, in March of 1999, as part of a collaboration among the Universitat Politecnica de Catalunya, other Spanish organizations, and JPL. The second set was obtained off North Carolina, USA, in October of the same year, by personnel working for the Naval Surface Warfare Center, Dahlgren Division. Afterwards, both data sets were made available for this study. In both cases, data were collected at least once per second.

Since the nature of what lies between receivers hardly affects GPS results, instead of using distant reference sites across the sea, it is just as valid to test the idea of positioning buoys in the deep ocean using readily available reference receivers installed far *inland*

In the case of the Llafranc test, the distant reference sites were International GPS Service (IGS) stations, and in the Duck test, some of the Continuously Operating Reference Stations (CORS) run by the National Oceanic and Atmospheric Administration (NOAA) in the USA. Data from both organizations is publicly available in the Internet as RINEX files. Data is stored in the IGS files every 30 seconds and in those from CORS, every five.

KINEMATIC DATA ANALYSIS

The results shown in this paper were obtained in sequential post-processing of phase and pseudo-range, using both a Kalman filter and a smoother procedure.

The short-baseline solutions were used for comparison purposes, and were obtained as already explained. For the long-baseline solutions, the L1 and L2 carrier phases were double-differenced between the rover and each reference receiver, and combined to form the ionosphere-free observable Lc. The same was done with the P1 and P2 pseudo-ranges. Selected Availability being on at the time, the positions of the buoys could only be estimated with precision at the measuring epochs of the reference receivers. The ones used for the long-range solutions run at a lower rate than those in the buoys (every 30 seconds for the Spanish test, and every 5 seconds for the US one). The Lc biases (a linear combination of the L1 and L2 integer ambiguities) were estimated as real numbers (i.e. "floated"). All this is standard procedure in long-baseline GPS solutions. (Recently, there have been successful attempts at resolving the L1 and L2 ambiguities with the roving receiver hundreds of kilometers away from any base station, using computed tomography to model and then correct the effect of the ionosphere on the GPS data [7].)

The following unknowns were estimated: (a) Corrections to the buoy preliminary instantaneous position (treated as three "white noise" states, with a 100 m *a priori* one-sigma precision per coordinate). (b) The biases in the Lc combination (treated as constants, each with a 10m *a priori* sigma). (c) The error in the tropospheric refraction correction at each site (a constant plus a slow random walk error in the zenith delay). (d) GPS satellite orbit errors, as pseudo initial state errors, using analytical orbit perturbation partials, and *a priori* sigma for the initial position and velocity according to the IGS SP3 file headers. Altogether, some 100 error-states were estimated in each case (to save computations and memory, orbit and bias states no longer active, were "recycled", yielding their places to newly activated ones). Data compression was also used to expedite computations.

The corresponding long-range GPS software developed by the first author runs under UNIX, LINUX, Windows 95, 98, and NT. The calculations for the Spanish test were made in an HP 9000/735 Unix workstation, and those for the US test in the same 266 MHz-Pentium II laptop used to write the final draft of this paper. For the US test, the total computer time was less than one minute for pre-processing and analyzing three hours of long-baseline data from three receivers.

TEST OFF LLAFRANC, IN CATALONIA, SPAIN

The CATALA campaign was conducted in March 1999 off the Catalonian coast near Begur Cape/Llafranc in the NW Mediterranean Sea. The main objective was to perform the absolute calibration of the TOPEX altimeter (side B) in the US/French oceanographic satellite TOPEX/POSEIDON using GPS on buoys. Other issues investigated were the calibration of GPS buoys, and mean sea surface mapping with GPS buoys. The campaign consisted of two reference stations on shore and two GPS buoys placed on the TOPEX/POSEIDON ground-track to get the instantaneous sea level. Two tide gauges were installed in the Llafranc harbor: an Aanderaa pressure sensor and a float gauge with a Thalimedes shaft encoder.

The satellite came over the buoys at 8:45 UTC on March 18, 1999, on an ascending pass, in orbit cycle 239. Results of this campaign, including the altimeter calibration, have been reported in [8], [9].

Figure 2. One of the two buoys used in the CATALA campaign, off the North East coast of Spain.

Figure 3. The two buoys being towed behind a small craft during the test.

The GPS buoys were designed at the Cartographic Institute of Catalonia using GPS antennas placed inside floats as shown in Figure 2. The antennas were connected to receivers in the towing ship by cables running along the tow ropes and suspended off small floats (Figure 3). Towing speed, during the three hours of the test, was kept at about 1 m/s. The receiver connected to one of the buoys did not perform adequately. Only measurements from the other receiver have been processed for this study.

Observations at the buoys and at the reference site in Llafranc were taken once every second (1 Hz.) As distant reference sites, two IGS stations in Europe were selected for their superior data during this period: "SFER" in San Fernando, southern Spain, and "GOPE" in the Czech Republic. They were 1010 km and 1268 km, respectively, from the "HOTE" site in the roof of a hotel in Llafranc, and just about as far from the buoys. All three fixed sites were placed in the same reference frame by tying HOTE to IGS stations in Spain.

DATA ANALYSIS AND RESULTS

First, GPS data from the short baseline HOTE to BUOY were analyzed to obtain a precise trajectory for the buoy connected to the one receiver that worked properly. The result was the position of the buoy, once every second (1 Hz), with the L1 and L2 ambiguities resolved. Because of the distance (14 km), the data were used in the form of ionosphere-free combinations Lc, corrected for biases calculated as combinations of the respective L1 and L2 ambiguities.

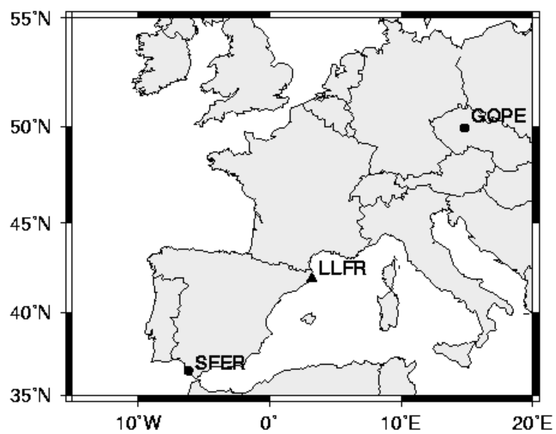

Figure 4. Location of the three reference sites used to analyze data from one of the CATALA buoys, which were never more than 20 km away from Llafranc.

The position of the buoy was re-calculated relative to the distant sites every 30 seconds, the IGS data rate, and the result was compared to the precise short-range trajectory. Figure 5 shows the differences between the trajectory relative to HOTE (14 km) and that relative to SFER (1010 km). Figure 6 shows the same comparison with both SFER and GOPE as reference sites (two baselines). The precise IGS ephemeris were used. Notice the lessened agreement with the short-range trajectory when using data from GOPE. The small jump at the start of the last half-hour could have been caused by an imperfectly corrected cycle-slip.

In the case of Figure 5, the 3-dimensional difference between short- and long-range solutions is 2.7 cm (mean) and 2.9 cm (r.m.s. about the mean), and in height it is 1.4 cm (mean) and 2.4 m (r.m.s. about the mean), for the 3 hours of the test. Corresponding numbers for the case of Figure 6: 3-dimensional, 3.3 cm (mean) and 5.7 cm (r.m.s. about the mean), height, 1.8 cm (mean), 3.5 cm (r.m.s. about the mean).

The tidal record from one of the gauges in the harbor of Llafranc was compared to the change in buoy height according to the short-range, 1 Hz solution, after using a 6-minute running average to eliminate the effect of waves. The actual tide, at the time, had just crested and was starting to go down. The tidal variation for the period was quite small, about 12 cm. Unfortunately, the mean GPS-determined height, corrected for the solid earth tide, showed also a small change, but in the opposite direction. This result diverged from the tidal record by 17 cm, or more than what one would expect to see from noise alone. No obvious explanation has been found for this. An independent short-range analysis of the same data, using different software, shows the same kind of problem (Marina Martinez Garcia of the Universitat Politecnica de Catalunya, personal communication.) The tidal record itself agrees well with a model derived from satellite altimetry (Richard Ray, NASA Goddard S.F.C., personal communication).

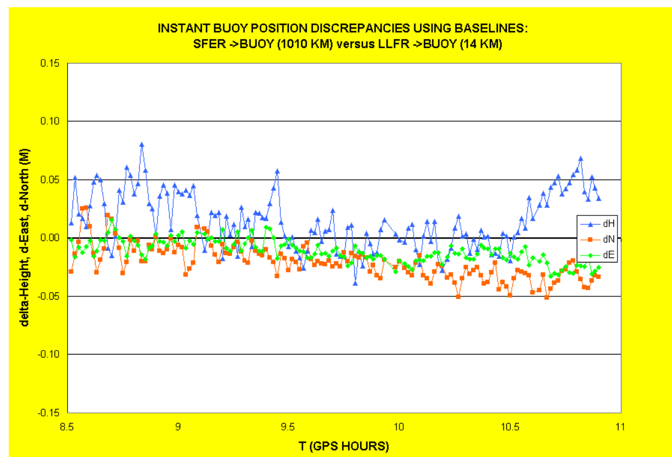

Figure 5. Comparing the trajectory of one of the buoys relative to: (a) nearby "LLFR", (b) far away "SFER".

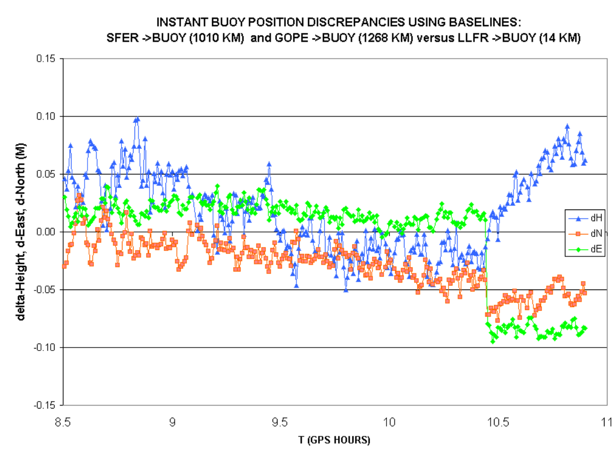

Figure 6. Same as Figure 5, but using both "SFER" and "GOPE" as distant reference stations.

Some plausible explanations for this disagreement with the local tidal record are: a problem with the buoy GPS data, a wind effect, and a lifting force caused by the active dragging of the buoy across the water, as it was under tow for the whole test. In the US test, where the buoy mostly floated passively in the surrounding water, was much nearer to the tide gauge, and the wind was calm, the mean sea height change observed with GPS agreed closely with the local tidal record.

TEST OFF DUCK, IN NORTH CAROLINA, USA

The second buoy test took place on 26 October 1999, at the initiative and under the direction of Dr. Alan G. Evans, of the Naval Surface Warfare Center, Dahlgren Division (NSWCDD), at the Army Corps of Engineers Field Research Facility (FRF) in Duck, North Carolina. GPS dual-frequency receiver data were collected at a buoy (site "BUOY") anchored at the seaward end of the very long FRF pier, and at a reference site atop a building ("FRFR"), 500 m away, near the pier's landing. The observing rate was 2 Hz. Aspects of the local test setup are shown in Figures 8, 9, and 10.

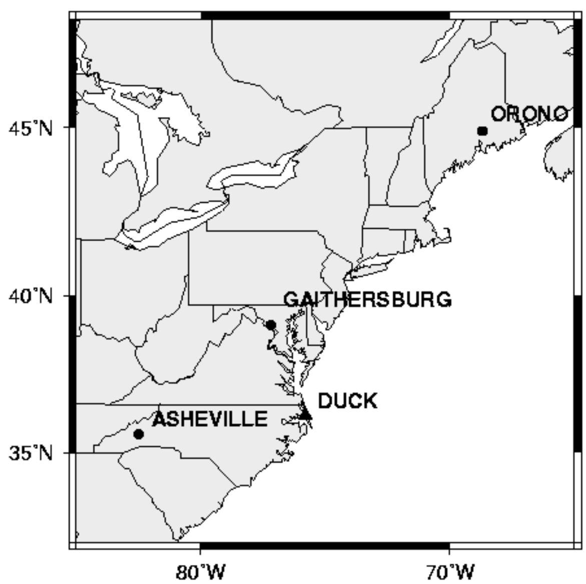

Figure 7. Duck and the distant CORS GPS sites. Duck is 352 km from Gaithersburg, 617 km from Asheville.

The far off GPS receiver observations, available at a 0.2 Hz rate, were downloaded over the Internet from the NOAA CORS sites in Gaithersburg ("GAIT"), Maryland, Asheville ("ASHE"), North Carolina, and "ORO1", in Orono, Maine. These were situated 352 km, 617 km, and 1138 km away from Duck, respectively (Figure 7).
All three land sites were put in the same reference frame by a precise static solution where the coordinates of the CORS sites were kept fixed to their published values, corrected for tectonic motion. A total of four hours of data were collected at the buoy, but only the last three hours were processed, because of reception problems earlier on. The distant sites were used as base stations for a long-range kinematic solution obtained every 5 seconds (the CORS data rate), and then compared to a short-range solution relative to "FRFR", near the pier's landing.

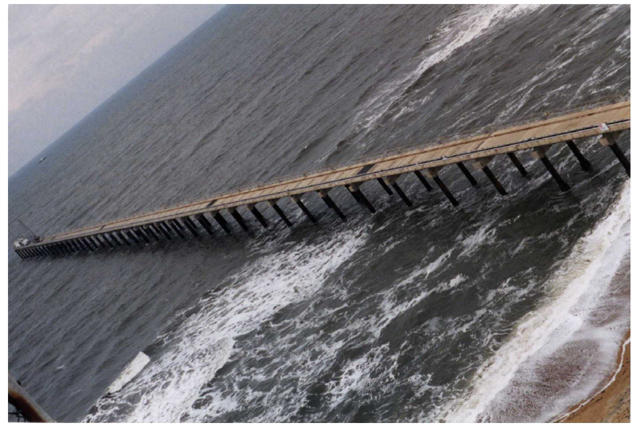

Figure 8. The Duck FRF pier seen from a nearby tower.

Figure 9. The buoy deployed near the end of the pier.

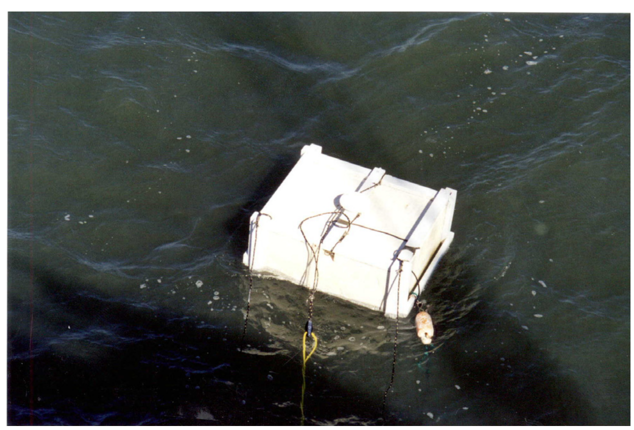

Figure 10. Close-up of the buoy showing the small, round GPS antenna on top. (Dimensions: 4' x 4' x 2')

The short-range solution had the L1 and L2 carrier phase integer ambiguities resolved on the fly. To get higher accuracy in this very short-range solution (500 m), only the unambiguous L1 phase was used to position the buoy.
The differences between short and long-range heights should reflect mostly errors in the long-range solution.

GPS-DERIVED BUOY HEIGHT AND LOCAL TIDE

Since 1978, the National Ocean Service (NOS) of NOAA has operated a primary tide station (No. 865-1370) at the seaward end of the FRF pier. A NOS acoustic tide gauge (Next Generation Water Level Measurement System, NGWLMS) provided water level data every 6 minutes. The observed tidal heights were used as "ground truth", comparing them to a 6-minute running average (to reduce the effect of waves) of the GPS-determined ellipsoidal height of the buoy, corrected for the Earth body tide (but not for ocean loading).

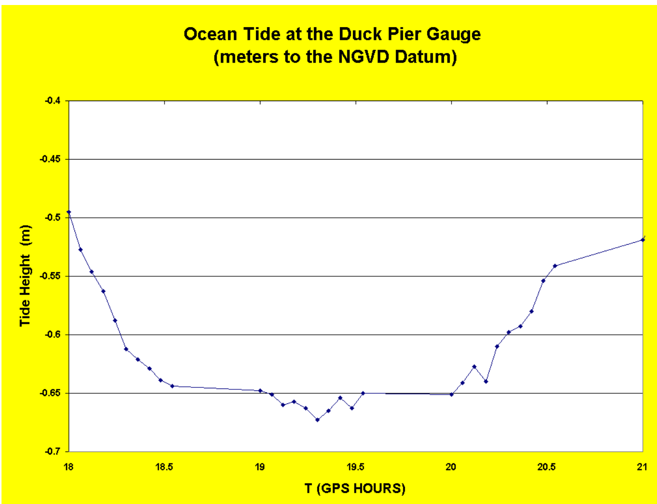

Figure 11. The change in sea height during the test, recorded at the local tidal station.

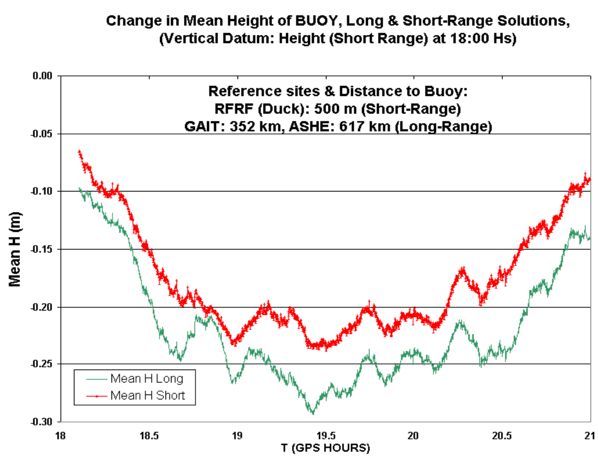

Figure 12. Change in buoy height from short- and long-baseline kinematic solutions. Short-range, relative to Duck (FRFR), long range, relative to GAIT and ASHE.

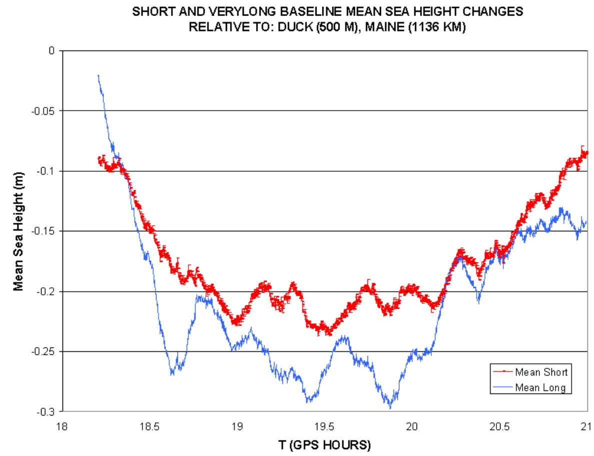

Figure 13. As in Figure 12, with the "ORO1" site in Maine used as distant reference.

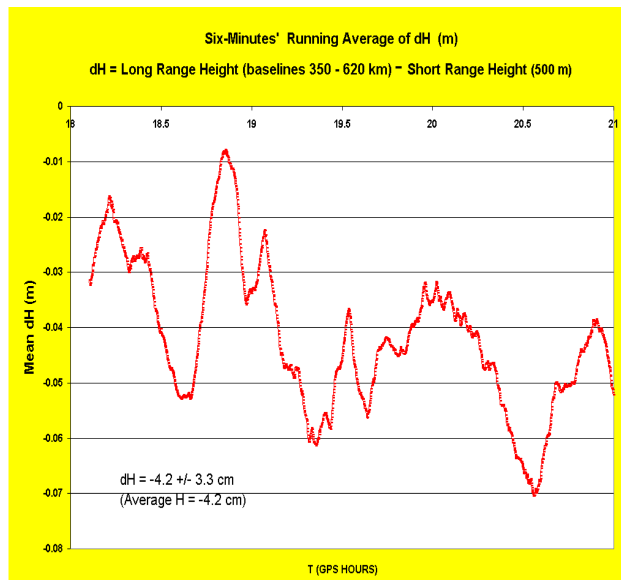

Figure 14. Discrepancies in estimated sea height change between short- and long-baseline solutions (for the case of Figure 12).

The tide-gauge observations were given relative to the US National Geodetic Vertical Datum. There was not enough information to establish their exact correspondence to the GPS heights. So only changes in height could be compared (Figures 11 and 12). The discrepancies between the short and the long baseline solutions can be seen in Figures 12, 13, and 14. The change in mean sea height according to both the short-baseline solution relative to Duck and the long-baseline solution relative to GAIT and ASHE agreed with the nearby tide-gauge to 5 cm (Figure 12). The agreement was 8 cm when ORO1 was the distant reference site (Figure 13). (A small part of the difference with the locally observed tide can be blamed on an imperfect solid earth tide correction, and the neglect of ocean loading.)

Over the three-hour period, the GPS mean sea heights relative to the nearby reference site (500 m away) are offset from those relative to ASHE and GAIT (352 km and 617 km) by -4.2 cm on average, and the maximum discrepancy is 5 cm (Figures 12 and 14). With the mean heights relative to ORO1, the average offset is -3.5 cm, and the maximum discrepancy is 8 cm (Figure 13).
If a potentially damaging tsunami (more than 10 cm high in deep ocean waters) could be detected from 500 meters away, it could also be detected from 1100 km away. Alternatively, the height measured with a satellite altimeter could be calibrated to better than 5 cm (a longer observing period would probably improve this result).

SPEEDING UP KALMAN FILTER CONVERGENCE FOR REAL-TIME USE

The post-processed results shown above correspond to a fully converged Kalman filter. The filter has to assimilate enough data to *converge* to a precise solution. The time needed for this should be kept as short as possible, since a tsunami (for example) could pass unnoticed while the calculated height of the buoy is still not precise enough to detect it. While clearly needed in real time, fast convergence is always desirable. Even in post-processing, frequent gaps in GPS reception may cause the filter to be re-initialized too often, preventing its proper convergence, and resulting in a filter/smoother solution that is not precise enough. (The final precision achieved with the filter is, by and large, also that of the whole post-processed trajectory calculated with the smoother.)
A kinematic solution wisely ignores the often poorly known dynamics of the vehicle. In the case of a craft floating on water, however, the use of a slow-varying mean sea-height constraint can shorten the convergence transient without introducing unwarranted assumptions as to how that craft otherwise moves. For a small buoy, the running average of its height, corrected for the solid earth tide, should approximate the wave-filtered, time-varying sea height measured with a tide-gauge, which changes gradually and predictably with time. In the long-range technique used here a constraint on the mean height is easy to implement, because of the use of *data compression* (averaging) to speed up calculations and economize other computer resources, such as hard disk space for scratch files [5]. The mean position of the vehicle, averaged over several minutes, is estimated before the instantaneous position. Given this, it is easy to create pseudo-observations of the form:

mean sea height(estimated) - mean sea height(model) = error in model(constant + random walk) + noise.

The "model" is the known value of the time-varying sea level at the location of the buoy. It is the sum of the long-term mean sea level, the geocentric tide (ocean tide + solid earth tide + ocean loading) and the inverted-barometer effect of atmospheric pressure (good models of mean sea level and tides are available for most of the oceans from the analysis of satellite altimetry). The model can be improved, over time, using the GPS-determined buoy heights. For this study, the "model" was a constant height chosen equal to the initial 6-minute average height according to the precise short-range solution. On the right hand side, the unknown constant represents the error in initial height, and the random walk represents the error in the change in height, both according to the model. The noise is the residual wave action left in the average.
For an averaging interval T_a seconds long, given approximately sinusoidal waves of dominant period T_w and peak-to-null amplitude A_w, and a data rate high enough to keep waves from becoming aliased into mean sea height changes, the (r.m.s.) value N_w of the residual wave-effect is:

$$N_w \leq T_w / (2^{3/2} \pi T_a) \; A_w$$

To be conservative, "≤" could be replaced with "=". Choosing: T_a = 120 seconds (a good compression interval for the solution, not for averaging waves), A_w ~ 2 m, and T_w ~ 20 seconds, then N_w ~ 4 cm (r.m.s.). Waves at the time of the test were much smaller, but this choice of amplitude was judged more realistic for open waters. The other (one sigma) uncertainties were chosen as follows: unknown constant, 10 cm (assuming good mean sea surface and tide models from satellite altimetry); random walk system noise, 3 cm $/(\text{min})^{1/2}$ (a one-sigma change in mean sea height of about 12 cm in 15 minutes.) The unknown constant had a larger uncertainty (30 cm) in the example of Figures 16, 17, and 18.

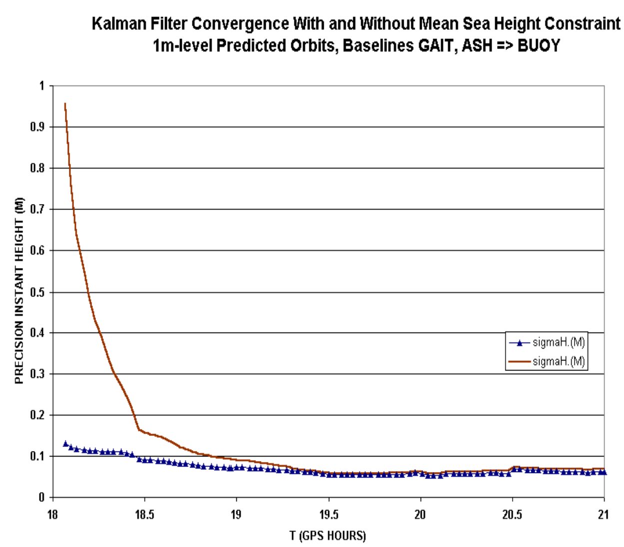

Figure 15. Convergence of the Kalman filter solution with and without the proposed mean height constraint. Plots show instantaneous vertical precision, in meters. Initially, the precision without the constraint is at the meter level.

The effect of the mean height constraint on the convergence of the Kalman filter can be seen in Figure 15. This figure shows the (one sigma) precision of the estimated *instantaneous* buoy height as a function of time (in meters): (1) for a purely kinematic (unconstrained) solution, and (2) for a mean-height constrained solution. (In the plots of Figures 15, 16, 17, and 18 the interval between points is 2 minutes, the same as the averaging interval used to compress the data.)

The convergence for height clearly improves with the constraint. The convergence in *horizontal* precision also improves markedly (not shown here). This happens because a constraint on the vertical direction also increases the precision of the estimated Lc biases, helping determine better the position along directions slanted towards the satellites. This, in turn, improves the horizontal precision.

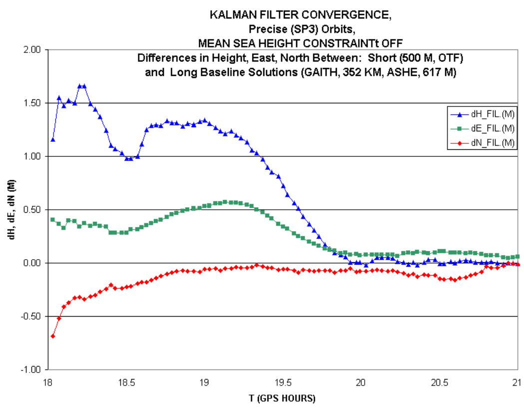

Figure 16. Difference between the short-range solution and the long-range solution relative to ASHE and GAIT, without the mean height constraint, using precise IGS orbits.

Here, since the filter is supposed to be operating in real time, the GPS satellite orbits have been given *a priori* uncertainties of 1 m in each initial coordinate. This assumes the availability of reasonably good predicted nominal orbits, and that the errors in those orbits are also estimated in the filter. Such orbits may be calculated at the central monitoring site, using data from its own stations, or else might be obtained from some future international service, such as the one being discussed within the IGS. In either case, solving for orbit errors simultaneously with the position of the buoy is probably needed to achieve sub-decimeter precision in real time.

Figure 16 shows the difference between the actual unconstrained Kalman filter solution relative to ASHE and GAIT, and the short-range solution relative to FRFR.

Notice the very slow convergence in this case: it takes about two hours before all three coordinates of the long-range solution are within 10 cm of the precise short-range one.

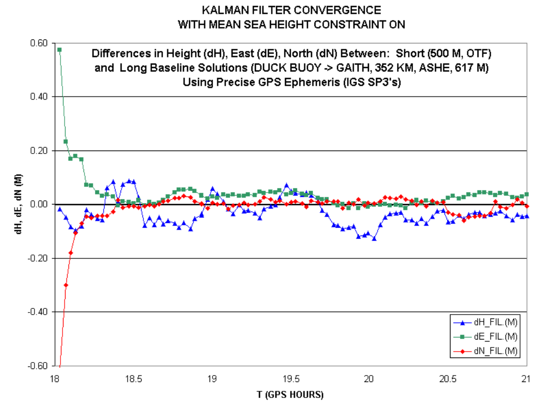

Figure 17. As in Figure 16, but using the mean sea-height constraint. Notice that convergence is much faster for all three coordinates, not just the height. Precise IGS orbits used.

Figure 17 shows the effect of imposing a mean sea height constraint. Notice that, as predicted by Fig. 15, all three coordinates now show a much faster convergence than without the constraint. In this case, the orbits used are precise (SP3) IGS ephemeris, and their errors are deemed too small to need estimating.

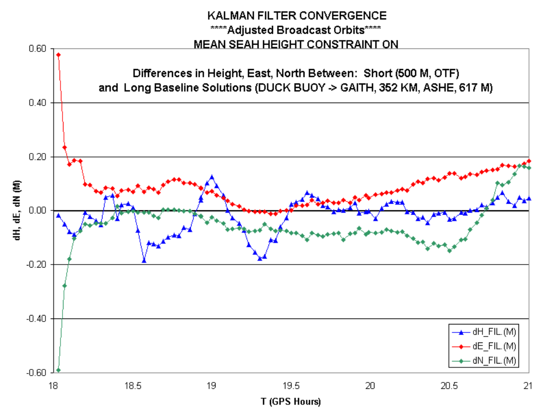

Figure 18. As in Figure 17, but using the broadcast ephemeris and estimating their errors at the same time as the trajectory of the buoy.

Figure 18 shows similar results, but using the ephemeris broadcast in the GPS Navigation Message, which are less precise than the IGS ones. These orbits are adjusted (their errors estimated) together with the buoy trajectory, the carrier phase Lc biases, and the tropospheric refraction correction errors. Comparing Figures 17 and 18, one notices that position errors for the buoy when adjusting the broadcast orbits are roughly twice the size than with the IGS precise orbits (without adjusting the broadcast orbits, the errors are considerably larger). In real-time operation, one may expect to use worse orbits than those of the IGS, but better ones than the broadcast ephemeris. Data from the receivers of a continuously operating network can be used to estimate the errors in the broadcast ephemeris, and the result can be radioed as corrections to users in the area.

To see to what extent the use of the height constraint biases the height in the post-processed (i.e., filtered and smoothed) long-range solution, constrained post-processed results were compared to their unconstrained counterparts. Their difference in height, over the three-hour run, had a mean of 1 cm, plus a variation of 7 mm r.m.s.

CONCLUSIONS

Results from two separate experiments in long-range kinematic positioning of buoys at sea, one in Spain, the other in the USA, indicate a precision of better than 10 cm r.m.s., 3-dimensional, at distances ranging from 300 km to more than 1000 km from the nearest reference receiver. The results from the test at Duck, in North Carolina, show agreement at the sub-decimeter level between the change in sea level according to both the short- and long-range GPS solutions, and to the local tide gauge. Adding a simple sea-height dynamic constraint to the kinematic formulation results in a much faster convergence of the Kalman filter, making the use of this constraint potentially valuable for precise applications of GPS to marine positioning, in real time as well as in post-processing.

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